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FULL-SCALE BLAST TEST RESPONSE OF PARTIALLY GROUTED MASONRY WALLS

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Full-scale Blast Test Response of Partially Grouted Masonry Walls

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ABSTRACT

This paper summarizes recent testing conducted as part of a collaborative research program between the Air Force Research Laboratory (AFRL), the Portland Cement Association (PCA), and the National Concrete Masonry Association (NCMA). The stated objective of the broader cooperative research program is “to develop blast protection data for concrete building products typically used in construction and to develop improvements to these designs as needed to improve blast resistance.” The most recent component of the program focused on the blast impulse load response of partially grouted concrete masonry unit (CMU) walls that minimally comply with the standards of the Department of Defense Unified Facilities Criteria (UFC) and other relevant non-DoD specifications. Three design sections were evaluated: (1) a 6-inch standard block masonry wall reinforced with #3 rebar at 32-inch nominal spacing, (2) an 8-inch standard block masonry wall reinforced with #4 rebar at 48-inch nominal spacing, and (3) a cavity wall consisting of the 8-inch standard reinforced CMU wythe, plus a 4-inch clay facing brick veneer with 2-inch thick extruded polystyrene rigid board insulation and a 1-inch air gap between the structural wythe and the veneer. The test program included (1) large-displacement static resistance testing under uniform pressure in a vacuum chamber and (2) full-scale explosion arena testing. During the static testing, displacements were recorded as each test panel was loaded to collapse, and the resistance function results were assessed against the resistance definitions assumed by standard blast design methodologies. Interior and exterior videography was also used to record the progression of failure. Subsequent to the static testing, three full-scale explosion arena tests were conducted; each experiment involved one each of the three test panel designs (nine total panels tested). Dynamic test instrumentation included pressure gages (reflected and free field), deflection gages (three locations for each test panel), and high-speed videography. This paper summarizes the masonry test program, important differences between the static and dynamic failure modes, and important differences between the responses of fully grouted and partially grouted CMU walls.

Keywords: blast, concrete masonry full-scale testing, large deflection, reinforced masonry, resistance function.

INTRODUCTION AND BACKGROUND

Over the past decade, the US Government has adopted construction requirements and incentives that promote energy efficiency and build green initiatives. The Energy Policy Act of 2005 [1] provided tax incentives and loan guarantees for energy solutions that could combat growing energy problems. It provides tax breaks for energy conservation improvements to homes and commercial buildings that make improvements to their energy systems. The Energy Independence Security Act of 2007 [2] was enacted “to move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, and vehicles, to promote research on and deploy greenhouse gas capture and storage options, and to improve the energy performance of the Federal Government, and for other purposes.” It provided new initiatives for promoting conservation in buildings and industry, and new standards and grants for promoting efficiency in government and public institutions. Furthermore, military facilities construction requirements such as the Anti-Terrorism and Force Protection (ATFP), Unified Facilities Criteria (UFC), and the Military Construction (MILCON) Transformation initiatives also emphasize building economy and energy efficiency.

Masonry has been used in building construction for thousands of years. Worldwide, masonry units come in many different sizes and shapes, and can be made with a variety of materials including concrete, clay, and glass. Masonry walls are site constructed using manufactured masonry units and site mixed mortar. The units are mortared together to various heights, and can be oriented to create aesthetically attractive patterns on exterior walls. Masonry can form structural elements (bearing walls, columns, or pilasters) and/or finished cladding systems. Masonry walls also typically increase the fire resistance of the wall system or structural elements. Masonry walls can be single- or multi-wythe, and the interior cells of the units comprising masonry walls may be empty or grouted. “Reinforced masonry” generally refers to placing steel reinforcing bars vertically within the interior cells, and then grouting only those cells (partially grouted) or all cells (fully grouted). Horizontal reinforcing can also be used in the form of rebar laid horizontally within grouted cells and/or as wire mesh joint reinforcement.

Concrete masonry units (CMU) are made from a mixture of portland cement and aggregates under controlled conditions and must meet the requirements of ASTM C90. The units can be made to various dimensions, but typically have nominal face dimensions of 8 inches high by 16 inches wide. CMU blocks are made in forms to the desired shape and then pressure-cured in the manufacturing plant. The blocks are categorized based on the weight (lightweight, normal weight and heavyweight). Normal weight or heavyweight blocks are used for structural masonry applications; lightweight units are used for non-load-bearing conditions or as veneers.

One of the most commonly used modern construction geometries for exterior walls is “cavity wall” construction. This type of construction generally comprises an exterior brick veneer, foam insulation, air space, and an interior structural wythe comprised of concrete masonry (Figure 1). The exterior veneer and interior wythe are connected by steel ties that come in many different geometries. Veneer walls are designed as “drainage walls,” where a drainage cavity is installed behind the masonry veneer to allow water that penetrates the masonry to flow down to the base of the wall and direct it to the exterior. This cavity must remain open to allow water to freely drain. The concrete masonry structural wythe may be unreinforced (grouted or not-grouted), reinforced but grouted in reinforced cells only (partially grouted), or reinforced and grouted in all cell voids (fully grouted). Furthermore, cavity wall systems may be “load bearing” or “non-load bearing,” depending upon whether the masonry is designed to resist gravity loads from above floors and frame, or simply used as interior or exterior in-fill partitions. They can serve as a simple exterior boundary or as part of a multi-wythe insulated wall. They may be designed and constructed with or without grouted and reinforced cells, which primarily depends upon out-of-plane loading demands.

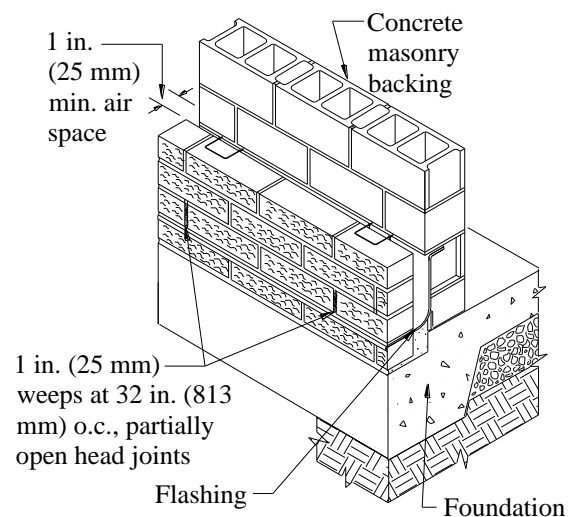


Fig. 1. Typical brick veneer cavity wall geometry (insulation not shown) (with permission from the National Concrete Masonry Association)

Exterior masonry walls must be designed to resist lateral loads from wind and earthquakes. In the US, loads are defined according to ASCE/SEI 7-05, “Minimum Design Loads for Buildings and Other Structures” [3]. MSJC 2008 / ACI 530, “Building Code Requirements for Masonry Structures (TMS 402-08/ACI 530-08/ASCE 5-08)” [4] is used for structural design of masonry. Design details can vary significantly between “West Coast” construction and “East Coast” construction, the details of West Coast construction typically being governed by earthquake-resistant design and East Coast construction being governed by hurricane wind forces. There are also subtle differences in construction approaches, such as in the common use of “A-block” in western states.

Government, military and diplomatic facilities are also commonly constructed with masonry exterior walls. In addition to standard wind- and earthquake-load resistance, these facilities must also be designed for security considerations and, pertinent to this effort, to withstand external explosions. For Department of Defense (DoD) buildings and facilities, the Unified Facilities Criteria (UFC) must be followed. Until recently, UFC 3-310-05A [5]

addressed the design of masonry structures for DoD construction. However, this was superseded by UFC 3-301-01 [6], which provides general structural engineering guidance and refers the designer to other standard specifications such as ACI 530 and the International Building Code [7].

Unfortunately, military and diplomatic facilities are targets of terrorist attacks. Populated public facilities such as residential buildings, office buildings, and restaurants are also targeted. The weapon most commonly used to target buildings and facilities is a vehicle that conceals several hundred to several thousand pounds of explosives, depending upon the size of the vehicle (commonly referred to as a vehicle-borne improvised explosive device, VBIED). Most of the dynamic pressure resulting from external explosions is first reacted by exterior walls. Therefore, ensuring that the exterior walls of a structure are able to withstand blast loading without producing deadly fragments is a critical part of minimizing injuries to building occupants. At the same time, large deformation ability facilitates blast energy absorption, reduces the magnitude of connection forces, and reduces loads transferred to the host frame. When subjected to airblast overload, unreinforced CMU walls break into pieces that are then propelled into the interior of the structure, causing severe injury or death to occupants. For these reasons, the DoD Antiterrorism/Force Protection Construction Standards [8] prohibits the use of unreinforced CMU exterior walls for new military construction.

Although blast load resistance has become much more of a design concern over the past decade, engineering for explosion loading still tends to be a specialty field in which a smaller subset of A/E firms focus. This is particularly true for the design of government, diplomatic, military, and high-visibility facilities and infrastructure that are considered to be at a greater risk of an explosion incident. Design of exterior walls to resist impulse loads is one of the fundamental steps in the design for external explosions. This can be accomplished by using advanced analysis approaches, such as central difference finite element solvers, but more commonly is accomplished through simplified analyses approaches such as pressure-impulse (P-I) diagrams and single-degree-of-freedom (SDOF) models. A primary resource for such tools is the US Army Corps of Engineers Protective Design Center (PDC). For wall element design, two commonly used tools are SBEDS (Single-degree-of-freedom Blast Effects Design Worksheet) [9, 10, 11] and WAC (Wall Analysis Code) [12]. For the most part, these tools tend to mirror methodologies and requirements established by the Unified Facilities Criteria (UFC), and in particular for wall element design, UFC 4-010 "Minimum Antiterrorism Standards for Buildings" [8] and UFC 3-340 "Structures to Resist the Effects of Accidental Explosions" [13]. Overall, the resources provided by the PDC and methodologies outlined in relevant UFCs are serving the blast engineering community well. However, there is need to augment and improve the resistances used by these tools towards representations of the blast energy absorbing capacities of modern multi-wythe insulated wall forms. There is also enormous opportunity to use modern energy efficient construction techniques to improve blast load design efficiency.

In 2005, the Air Force Research Laboratory (AFRL) initiated a collaborative research consortium with US concrete industry professional associations interested in advancing the state-of-the-art knowledge and design of their product interests for protective structure applications. The stated objective of the research that would be performed under this program was "to develop blast protection data for concrete building products (e.g., insulated form walls, precast/prestressed panels, tilt-up panels, masonry components, autoclaved concrete components, cast-in-place forming systems, etc.) typically used in construction and to develop improvements to these designs as needed to improve blast resistance." Industry associations represented included: the Portland Cement Association (PCA), Precast/prestressed Concrete Institute (PCI), Tilt-Up Concrete Association (TCA), Insulating Concrete Form Association (ICFA), Concrete Foundations Association (CFA), National Concrete Masonry Association (NCMA), and the National Ready Mixed Concrete Association (NRMCA). Other government agencies involved in protective design R&D that were present at initial meetings included the Air Force Civil Engineering Support Agency (AFCEA) and the US Army Engineering Research and Development Center (USA-ERDC).

Over the past four years, many tests, both static and dynamic, have been conducted. Blast resistance of multi-wythe masonry construction is one of the topic areas of this program. Therefore, this paper summarizes the investigation of the blast load resistance of multi-wythe insulated masonry walls. This comprehensive investigation included (1) vacuum chamber (uniform pressure) static resistance testing, (2) full-scale dynamic testing (explosion-generated loads), (3) high-fidelity finite element modeling, and (4) the development of engineering-level analytical models. Specific emphasis was placed on determining the potential of foam insulation to attenuate impulse load energy and reduce the overall flexural response of the system. Single-wythe designs and double-wythe (cavity wall) designs with 2-inch extruded polystyrene board insulation were tested. The structural wythe comprised standard 6- or 8-inch

concrete masonry blocks, and the veneer of the double-wythe configurations was typical clay brick. All cells of some test panels were fully grouted and reinforced based on a 110-mph wind load design, while other panels were minimally reinforced with grout placed only in the cells containing vertical reinforcement. Finite element simulations and parametric studies were conducted using LS-DYNA. Two-degree-of-freedom calculations were used to examine the loads transferred through the ties that attach the brick veneer to the CMU wythes. Post-test forensic analyses were used to evaluate the extent of foam crushing and overall composite behavior that occurred during full-scale blast tests.

TEST PROGRAM

The masonry test program was conducted in two test series. The primary distinction between the two series is that Series I focused on the resistance of relatively robust fully grouted walls, whereas Series II focused on the behavior of masonry walls that minimally meet relevant UFC standards (partially grouted, minimally reinforced). Both series involved full-scale static testing under uniform pressure using a vacuum chamber and full-scale dynamic testing using explosion-generated impulse loads. The Series I testing was completed in late 2007, and Series II testing was completed in December 2009. Specifications common to each of the test panel designs included:

- Concrete Masonry Units: ASTM C 90, light or medium weight, 8 inch, standard square end units
- Clay Brick: ASTM C 216, Grade SW, Type FBS, standard 4-inch facing brick
- Mortar: ASTM C270, Type S Mortar, with 3/8-inch joints
- Grout: ASTM C 476, 3000-psi coarse grout
- Reinforcing Steel: ASTM 615, Grade 60 and ASTM A 706, Grade 60
- Joint Reinforcement: ASTM A 951 , W1.7 (9 gage) ladder, located every-other course (16-inch vertical spacing)
- Veneer Ties: ASTM A 82 (Galvanized), W2.8 Double Eye and Pintle, 16-inch horizontal and 16-inch vertical spacing
- Foam Insulation: rigid, closed-cell XEPS thermal board insulation complying with ASTM C 578-95 Type X, minimum density of 1.35 pcf, minimum compressive strength of 15 psi (ASTM D 1621-94)

At each stage of construction, material properties were quantified using relevant standard testing methods, including masonry prism compressive strength (ASTM C 1314), mortar density (ASTM C780), mortar compression (ASTM C780), grout compression (ASTM C 1019), grout density (ASTM C 1019), and rebar tensile strength (ASTM A 370).

Series I involved two cavity wall section designs: 1) a conventional 110-mph Exposure C veneer section using standard concrete masonry units and 2) an identical section except that A-block CMUs were used. A-blocks are standard CMU blocks minus one end web. Both of these sections were fully grouted and reinforced with #5 rebar spaced nominally at 48 inches. Therefore they do not alter the section strength, but offer construction advantages as there is no need to lift them over vertical reinforcement bars during construction. A “control wall” was also tested that consisted of a fully grouted, single-wythe, 12-inch CMU wall reinforced with #5 rebar. The control wall was designed to have equivalent mass and flexural capacity as the other two cavity walls.

Series II designs were similar in construction materials and overall dimensions. However, the objective of Series II testing was to explore the resistance of masonry cavity walls that are constructed to meet the minimum requirements of UFC 3-310-05A, “Masonry Structural Design for Buildings.” Therefore, only the reinforced cells were grouted and #4 rebar was used instead of the #5 rebar used in Series I. Also, to further examine resistances of minimally reinforced walls and response to extreme loading, test panels using 6-inch concrete masonry and #3 rebar were constructed. Therefore, three test panels were considered in the Series II tests: (1) 6-inch standard block masonry reinforced with #3 rebar at 32-inch maximum spacing, (2) 8-inch standard block masonry reinforced with #4 rebar at 48-inch maximum spacing, and (3) same as the 8-inch panel, plus a 4-inch clay facing brick veneer with 2-inch thick extruded polystyrene rigid board insulation and a 1-inch air gap between the structural wythe and the veneer.

STATIC TESTS

Each test panel was carefully moved to a vacuum chamber reaction frame for uniform pressure application. The vacuum chamber uses a pump to displace air from inside the chamber, decreasing the pressure in the chamber and thereby creating a uniform load across the front wall surface (Figure 2). To produce the necessary sealed

environment, a rubber membrane was clamped over the exterior of the test panels. Aluminum flashing was attached to the outside of the chamber under the membrane to cover gaps between the wall and the frame so the rubber membrane would not be pulled into gaps during testing. Deflections of the inside surface of each panel were measured using string potentiometers at five locations along the inside of the wall. The cavity wall brick veneer deflections were also measured using external potentiometers. Gaps between the wall and the frame were filled with mortar so that the wall would be simply supported at the bearing surface and would not rotate during testing. The inside of each wall was painted white to create contrast so that cracks could be easily seen. The inside pressure was measured with two sensors. The deflection rate of the test panels was monitored and adjusted as load was increased so that failure progressed gradually.

In general, the failure of the walls under static pressure loading was initiated by a crack at the mortar joint nearest to the mid-height of the panel, followed by additional mortar joint cracks above and below the first crack. The cracks spanned horizontally across the full width of the wall. The walls continued to resist load as the walls moved inward and the cracks grew in width and number. Eventually, the walls collapsed due to self weight. In some cases, the dowels welded to the test frame fractured when the panel collapsed; the failure was within the dowel, and not at the welds. The overall resistance responses are summarized in Figure 3.



Fig. 2. View of the vacuum chamber, including deformed test panel

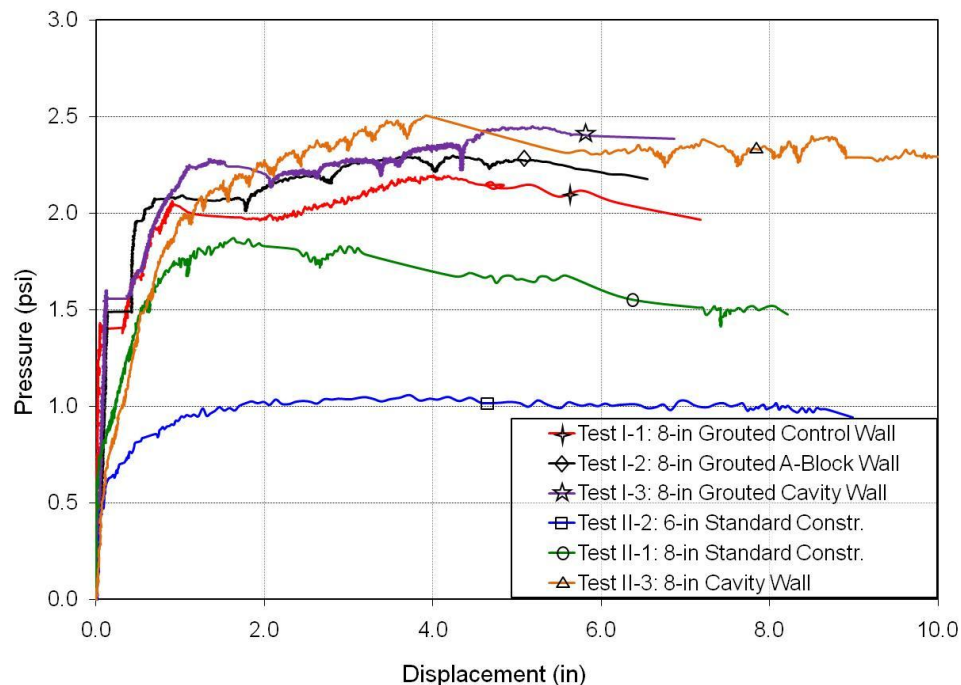


Fig. 3. Static resistance function comparison

DYNAMIC TESTS

Six of the Series I test panels were tested in three experiments (two each in three detonations), and nine of the Series II test panels were tested in three experiments (three each in three detonations). Arena experiments were conducted by positioning an explosive charge directly perpendicular with the middle of the center panel. For each experiment, the amount of explosive and/or the distance between the explosive source and the test panels was varied so that the test panels would be subjected to a designed loading. Data collected included (1) dynamic deflections, (2) pressures, and (3) videography. The overall test set-up and layout of instrumentation is illustrated in Figure 4 and an image showing the Series II panels ready for testing is shown in Figure 5. After completion of each test, the residual failure condition of each test panel was carefully documented with still photography.

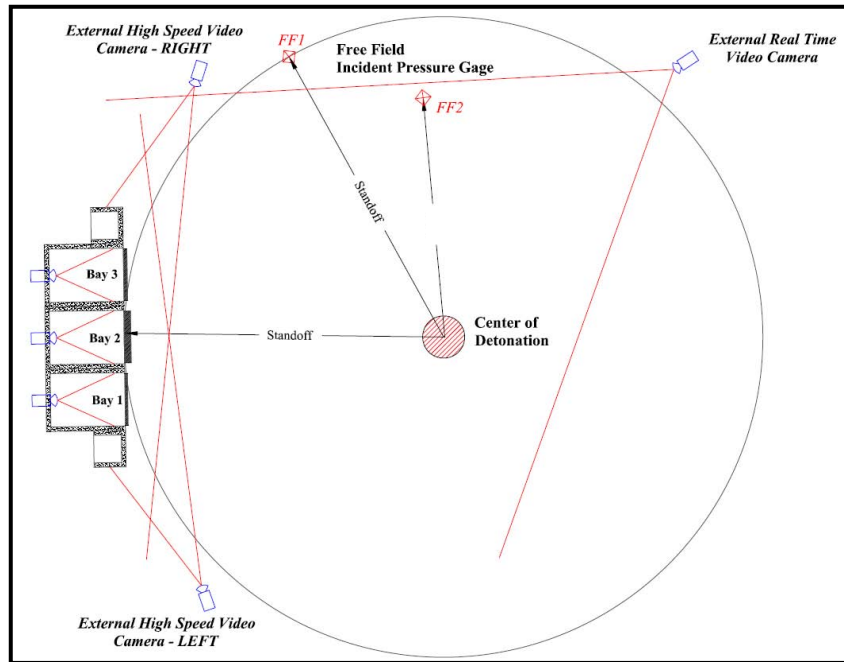


Fig. 4. Test arena and instrumentation layout



Figure 5. Test panels ready for dynamic loading

In general, the fully grouted test panels were able to take significant deflection in a uniform flexural action. Even under extreme loading, there was no significant breaching and the panels remained stable. The clay brick veneer remained in place and translated with the structural wythe. The ties that connect the veneer to the structural wythe were sufficiently strong to transfer the force from the veneer to the structural wythe, but their geometry does not transfer enough shear resistance for the cavity wall to behave compositely. Furthermore, post-test forensic analyses indicated that, since the veneer ties have sufficient rigidity to transfer the dynamic force from the veneer to the structural wythe, the insulation was not significantly crushed, and therefore unable to play a significant role in absorbing blast energy. An example of the fully grouted test result is provided in Figure 6.



Fig. 6. Example of a fully grouted masonry wall test result (exterior view – left; interior view – right)

The Series II experiments (partially grouted panels) revealed failure modes significantly different from those of the Series I fully grouted panels. Breaching occurred between the columns of grouted and reinforced cells. Also, the brick veneer collapsed in front of the test panels in the two larger loading experiments. An example of the partially grouted test result is provided in Figure 7.



Fig. 7. Example of a fully grouted masonry wall test result (exterior view – left; interior view – right)

SUMMARY AND CONCLUSIONS

This paper highlights the motivation, methodology, and observations resulting from a comprehensive investigation of the resistance behavior of multi-wythe insulated masonry walls subjected to blast loads. The overarching objective of the program was to develop data for multi-wythe insulated masonry wall systems typically used in construction that could improve blast resistance design and construction methodology. The broader investigation included (1) vacuum chamber (uniform pressure) static resistance testing, (2) full-scale dynamic testing (explosion-generated loads), (3) high-fidelity finite element modeling, and (4) the development of engineering-level analytical models. Predominant observations included (1) that the ties connecting the veneer to the structural wythe transferred the blast load forces, precluding the opportunity for the foam to undergo significant crushing and energy absorption, (2) there are no significant differences in resistance between A-block and conventional block construction, and (3) there are very important differences in failure modes that occur between fully grouted and partially grouted masonry walls when subjected to explosion-generated impulse loads. The testing described herein is now being used to assess current blast design and analysis practice and develop recommendations for improving relevant blast design doctrine.

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